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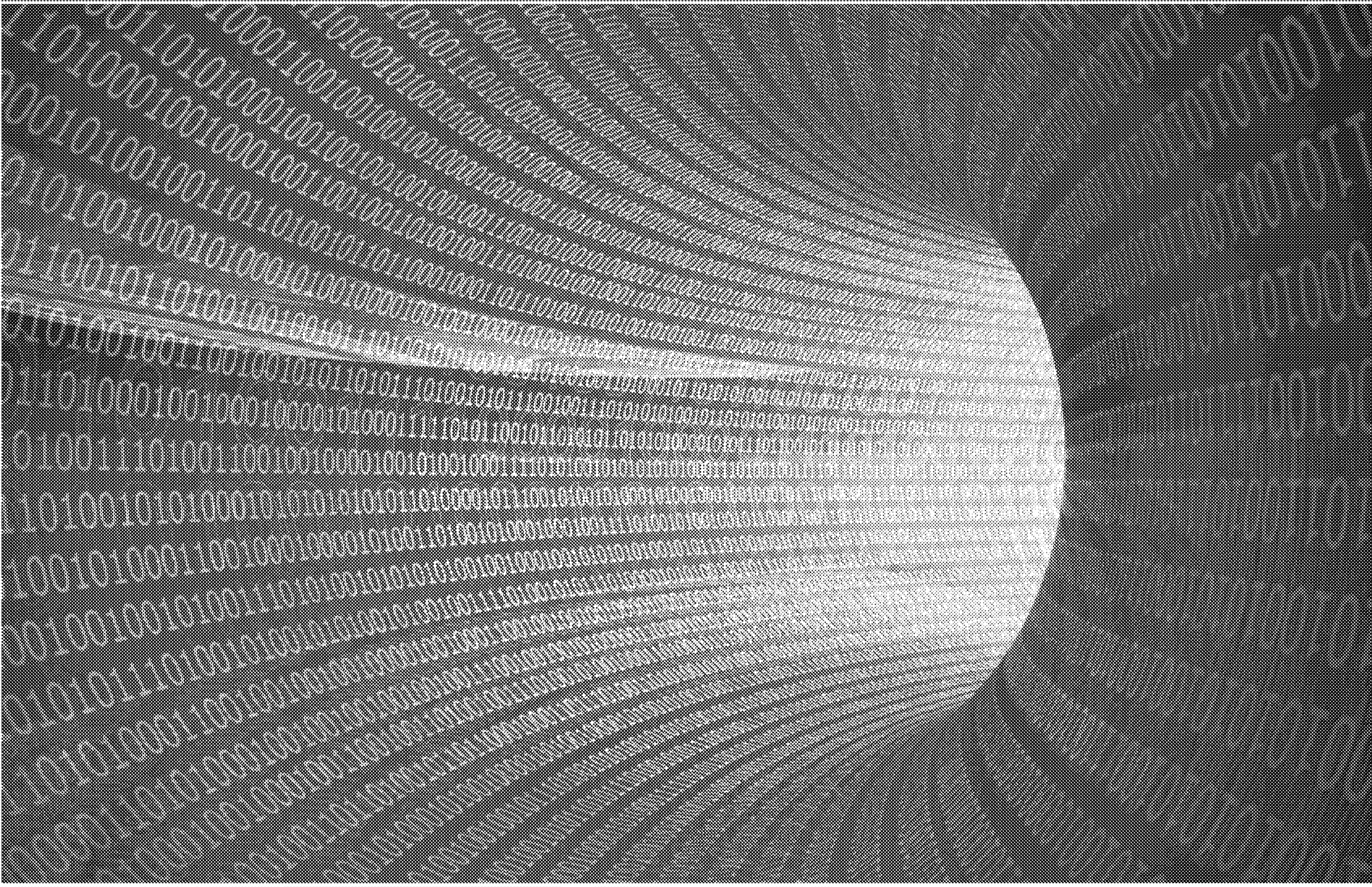

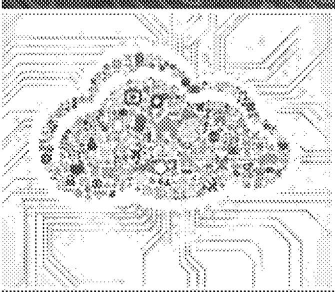

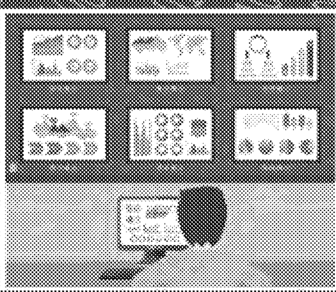

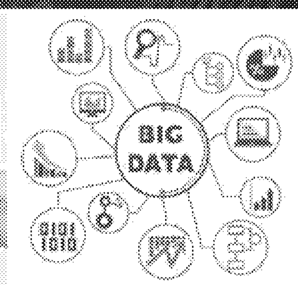

Smart Data Infrastructure for Wet Weather Control and Decision Support

U.S. Environmental Protection Agency
Office of Wastewater Management

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CONTENTS

APPENDIX A: CASE STUDIES

Disclaimer

The material and case studies presented in this document are intended solely for informational purposes. This document is not intended, nor can it be relied on, to create any rights enforceable by any party in litigation with the United States. Case studies used in this document are unique and site-specific, and they may not be as effective as demonstrated. This document may be revised or updated without public notice to reflect changes in the technologies and to update and/or add case studies. The U.S. Environmental Protection Agency (EPA) and its employees do not endorse any products, services, or enterprises.

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Acronyms and Abbreviations

CFR	Code of Federal Regulations
CMOM	Capacity Management Operation and Maintenance
CPU	Central Processing Unit
CSO	Combined Sewer Overflow
DSS	Decision Support System
EPA	U.S. Environmental Protection Agency
FOG	Fats, Oils, And Grease
GUI	Graphical User Interface
ICS	Industrial Control System
IoT	Internet of Things
I/I	Inflow and Infiltration
IT	Information Technology
KPI	Key Performance Indicator
LTCP	Long-Term Control Plan
MMSD	Milwaukee Metropolitan Sewerage District
MSD	Metropolitan Sewer District (Louisville)
MSDGC	Metropolitan Sewer District of Greater Cincinnati
O&M	Operation and Maintenance
PLC	Programmable Logic Controller
PWD	Philadelphia Water Department
RTC	Real-Time Control
RTDSS	Real-Time Decision Support System
SAWS	San Antonio Water System
SCADA	Supervisory Control and Data Acquisition
SSO	Sanitary Sewer Overflow
WWTP	Wastewater Treatment Plant

Glossary

Agent-Based Control: System with locally interacting components that achieve a coherent global behavior. Through the simple interaction of buying and selling among individual agents, a desirable global effect is achieved, such as fair allocation of resources.

Big Data: Data sets that are so large or complex that traditional data processing application software is inadequate to deal with them.

Cloud: Large-scale, offsite data storage facilities.

EPA SUSTAIN: Framework for the placement of best management practices in urban watersheds.

Gray Infrastructure: Engineering projects that use concrete and steel.

Green Infrastructure: Projects that depend on plants and ecosystem services.

Internet of Things: Process in which hardware is connected to a network (the internet) so that it can better communicate with other systems.

Long-Term Control Plan: Written strategy required by the Clean Water Act for communities with combined sewer systems to reduce and/or eliminate combined sewer overflow discharges in the long term.

Machine Learning: Data analytic method used to devise complex models and algorithms that lend themselves to prediction. This is also known as predictive analytics. There are many algorithms available.

Model Predictive Control: Model-based control strategy that predicts the system response to establish a proper control action. This strategy explicitly uses a mathematical model of the process to generate a sequence of future actions within a finite prediction horizon that minimizes a given cost function.

Real-Time Control: The ability of water infrastructure (valves, weirs, pumps, etc.) to be self-adjusting or remotely adjusted in response to current weather conditions.

Smart Water and Smart Data Infrastructure: The ecosystem of technology tools and solutions focused on the collection, storage, and/or analysis of water-related data.

1. Introduction

Rain and snowmelt (referred to as wet weather conditions) can significantly increase flows at wastewater treatment facilities, creating operational challenges and potentially affecting treatment efficiency, reliability, and control of treatment units at these facilities.

Current approaches to wet weather control rely primarily on gray or green infrastructure, or a combination of the two. In recent years, however, municipalities and utilities have been considering how they can take advantage of technological advances to improve their operations and infrastructure. These advances include:

- Faster computer processing and network speeds, providing ready access to reliable information for informed decisions.
- Smaller, more accurate, and less expensive sensors.
- Low-cost storage of large quantities of data.
- The advent of the "internet of things" (IoT), allowing sensors to be connected over large geographic areas.
- Smaller, higher-capacity batteries and photovoltaics, reducing dependence on permanent hard-wired power sources.
- Wireless transmittal of acquired data, reducing the need for continuous or dial-up hard-wired communications systems.

This document focuses on how municipalities, utilities, and related organizations can use advances in technology to implement "smart data infrastructure" for wet weather control—that is, how they can use advanced monitoring data to support wet weather control and decision-making in real time or near real time. Case studies about communities that have done this across the country are included as appendices and referenced where applicable throughout the report.

What Is in This Document?

This document summarizes key aspects of utility operations where smart data systems can provide significant benefits. It is organized as follows:

Section 2 presents an overview of smart data infrastructure, its relationship with green and gray infrastructure, its benefits, and a general "roadmap" for implementation.

Section 3 describes technologies applied specifically to wastewater collection and stormwater systems and key considerations for selection, design, implementation, and operations and maintenance requirements.

Section 4 describes the use of smart data infrastructure to promote collection system optimization, as well as long-term control plan implementation, modification, and development.

Section 5 discusses the use of real-time control systems to maintain and meet operational objectives.

Section 6 discusses data management, data sharing, and public notification when using smart data systems.

Section 7 describes data analysis in smart data systems, including data validation/filtering and the use of key performance indicators.

Section 8 discusses data visualization and decision support systems.

Section 9 discusses the future of data gathering technology for wet weather control and decision-making.

Appendix A includes 11 case studies about communities across the country that have implemented smart data infrastructure technologies.

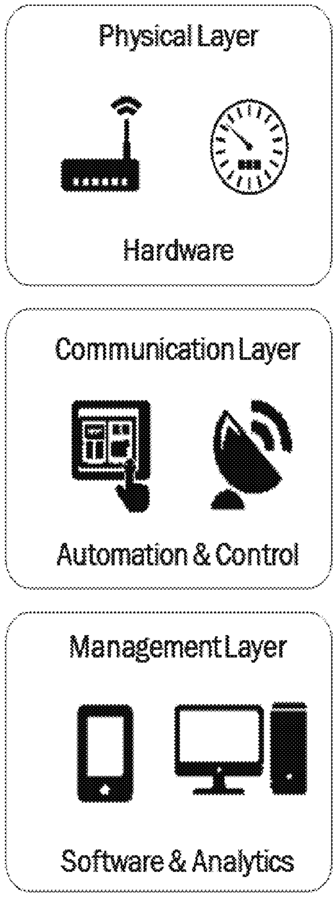
2. Smart Data Infrastructure

Smart data infrastructure is the integration of emerging and advancing technology to enhance the collection, storage, and/or analysis of water-related data. These solutions can generally be grouped into a framework that consists of hardware, communications, and management systems.

- **Hardware** includes the devices that measure and collect water-related data, such as level meters, flow monitors, valve actuators, and pump-run monitors.
- **Communications** refers to networks, including wireless communications, that migrate data from the hardware to the systems that perform analysis.
- **Management** refers to the software tools and analytical solutions that perform analysis and provide actionable information. It also includes data visualization to give managers real-time information for decision-making and to communicate with the public.

Smart data infrastructure leverages hardware, communication, and management analytics to provide real and tangible benefits to utilities, including:

- Maximizing existing infrastructure and optimizing operations and responses to be proactive, not reactive.
- Providing savings in capital and operational spending.
- Improving asset management and understanding of collection and treatment system performance.
- Improving long-term control plan (LTCP) implementation, modification, and development.
- Meeting regulatory requirements.
- Prioritizing critical assets and future capital planning.
- Providing the ability to better optimize collection system storage capacity to reduce peak flows and the occurrence of overflows.
- Enabling effective customer service and enhancing public notification.



Smart data infrastructure can be used to inform operational decisions that ultimately improve the efficiency, reliability, and lifespan of physical assets (e.g., pipes, pumps, reservoirs, valves). According to Global Water Intelligence Magazine, implementing digital solutions by consolidating monitoring, data analytics, automation, and control could potentially generate up to $320 billion in cost savings from the total expected capital expenditures and operating expenses for different water and wastewater utilities over the five-year, 2016–2020 period (GWI 2016).

The potential cost savings and other factors, such as regulations related to water quality, will likely stimulate the water industry to invest in smart data infrastructure and increasingly adopt the management of data-driven monitoring and control systems in the operation of various combined sewer, separate sewer, and municipal separate storm sewer systems.

In the future, data feeds and cognitive computing could significantly assist system managers by providing near-instantaneous support information for many of the routine and immediate response decisions that must be made in both the municipal and industrial sectors. Transformation may help water and wastewater utilities take advantage of innovations and opportunities in future operation and maintenance (O&M) (see Figure 1).

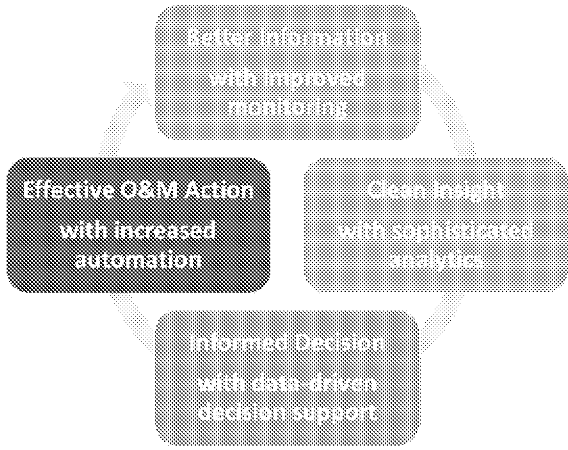


Figure 1. Better information and data can lead to more effective O&M

Roadmap for Implementing Smart Data Infrastructure

There are few, if any, insurmountable technological barriers to implementing the various technologies described in this document. Real-time control technology (Section 5), for example, has been around for nearly 30 years. While its implementation in collection systems remains relatively limited, the effectiveness of real-time control technology has been proven in many successful applications in wastewater treatment plants (U.S. EPA 2006).

When selecting technology and level of complexity, it is important to understand the utility's priorities and needs (e.g., O&M, information technology, security, data usage requirements). It is also important to remember that smart data infrastructure is scalable. Utilities can start small, applying technology that is compatible with the utility's existing capacity to ensure full acceptance and utilization of that technology, then move toward a more comprehensive approach with higher degrees of performance.

Regardless of the size or age of their infrastructure, utilities can benefit from this general roadmap for implementing smart data infrastructure:

1. **Vision for a utility of the future:** Imagine how data, assets, and technology could be leveraged to benefit the utility.
2. **Schedule:** Understand the capacity and timeframe for staff to accept change.
3. **Technology evaluation:** Validate data, prove benefits, and understand delivery.
4. **Detailed planning:** Seek funding and develop an implementation plan.
5. **Phased implementation:** Deploy the technology and associated platform.
6. **Continuous improvement and innovation:** Evaluate phase 1 performance and adapt the planning if necessary.

Key considerations for developing and implementing the roadmap include the following:

- Ensure organizational commitment for staffing and budget needs. There will be initial investment, as well as annual costs associated with the adoption of a technology.
- Communicate to ensure buy-in and support from all levels of management and foster strategic partnerships.
- Establish clear authority, roles, responsibilities, and communication channels.
- Define performance expectations.
- Educate and integrate team members early in the project.
- Provide continuous training and technical support to build the existing workforce's capacity and attract a new generation of workers.

3. Smart Data Infrastructure and Technologies: Information Inputs

Smart data infrastructure can generate highly informative data sets to support wastewater and stormwater collection system decision-making. These data sets help to answer critical questions that allow operators to maximize the effectiveness and efficiency of system operation (Figure 2); however, the usefulness of the data generated relies on accurate and relevant information inputs.

The following sections describe specific strategies and technologies for generating useful wastewater and stormwater collection system data, including key considerations for selection, design, implementation, and O&M. These strategies and technologies include:

- Continuous monitoring (Section 3.1)
- Level monitoring (Section 3.2)
- Flow monitoring (Section 3.3)
- Rainfall monitoring (Section 3.4)

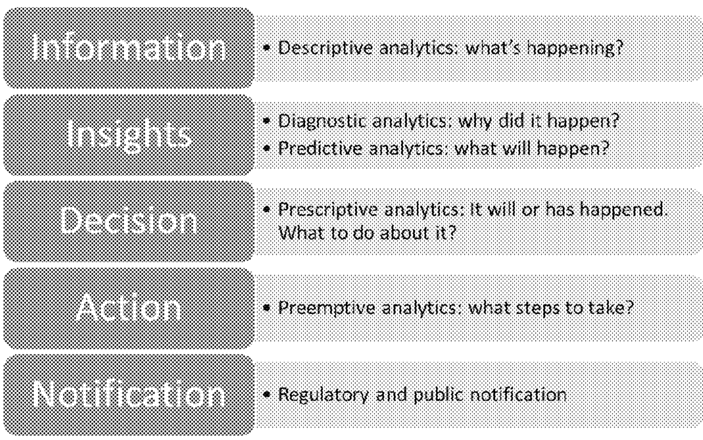


Figure 2. Operational process supported by information inputs

3.1 Continuous Monitoring

Continuous monitoring refers to permanent monitoring systems that report data back to a central system for use. The physical quantities to be monitored in a wastewater and stormwater collection system for proper operation and control are relatively basic and typically consist of flows, water levels, and rainfall conditions for dry and wet weather operations. In addition, equipment (such as pumps, gates, and valves) status needs to be monitored to ensure safe O&M.

Continuous monitoring when combined with proper data analytics and effective visualization can generate significant O&M savings by providing real-time insight into system conditions, which allows operators to prioritize asset management with effective targeted maintenance. Some examples include level trend detections that trigger alarms for equipment maintenance (e.g., cleaning), proactive inflow and infiltration (I/I) risk assessment, and data-driven work scheduling and asset management.

Continuous Monitoring in Practice

Milwaukee Metropolitan Sewerage District (MMSD) is using continuous monitoring to monitor the performance, value, and health of green infrastructure throughout the city. MMSD is monitoring 11 separate sites, including installations in public rights of way, allowing managers to see the combined and individual performance of green roofs and bioretention cells in real time. Every storm is recorded, performance can be reported in aggregate or by event, and the data can be used to fine-tune maintenance intervals and maximize performance.

Key considerations for continuous monitoring of wastewater collection systems include the following:

- The nature of wastewater systems presents a harsh and largely variable environment for monitoring equipment.
- The selection and installation of equipment needs to consider physical and hydraulic conditions, humidity, grit, sedimentation, debris, and corrosion, as well as confined spaces and maintenance access. For example, permanent monitoring equipment should meet explosive zone classifications.
- The advertised measurement accuracy of any sensor may not represent actual performance; as such, it will need to be calibrated/verified.
- Maintenance requirements, as well as hydraulic and physical conditions around the monitoring equipment, should be considered to balance out the increase in cost and complexity to provide accurate measurements. For example, forgoing some level of accuracy by selecting equipment with easier maintenance needs can ensure more reliable readings.

3.2 Level Monitoring

Multiple technologies are used to monitor water level in wastewater infrastructures. The most common types of sensors are pressure transducers, ultrasonic level meters, microwave meters, and capacitive probes. Other discrete devices for specific level detection, such as floating devices and vibrating level sensors, could be used in some cases. The most important criteria for selecting a specific technology will depend on the environment and infrastructure configuration where level must be monitored. More precisely, conditions such as the presence of turbulences and sedimentation in the water or the presence of fats, oils, and grease (FOG); foam; and obstacles in the air space above the monitoring location must be considered to select appropriate technologies.

Pressure transducers need to be submerged in the water where the level must be monitored; they are therefore convenient for applications where sedimentation is not a significant issue. They are typically used where water can be turbulent at the location of measurement. Stilling wells are usually recommended to install pressure probes away from potential debris in the water flow and for easier maintenance.

Ultrasonic level meters are also very common in wastewater applications and consist of installing a probe mounted above the water surface. They are usually preferred whenever space is available above the location where monitoring is needed. Multiple makes and models are available on the market. Ultrasonic sensors are recommended where minimal obstacles, FOG, or foam is present above the surface of the water. The sensor must be mounted far enough from sidewalls to avoid bad readings due to ultrasonic soundwave reflections.

When monitoring space is small or when FOG can be found in the air above the water surface, Doppler **radar microwave meters** are recommended because they use a narrower signal beam that improves the reliability of the measurement.

Capacitive probes are particularly suitable for multi-point water level monitoring and are preferred when a high spatial resolution (of a few millimeters) is necessary (e.g., for a reliable evaluation of stored volumes in big and flat storage facilities). The main advantages of these probes are that the sensors are easy to clean and can handle temperature and pressure variations. However, these sensors can significantly disturb the flow and should not be used in small pipes.

In general, sensors located above the water surface have less O&M, but are subject to corrosion and may experience issues with ice in cold environments.

For locations where monitoring the water level is critical, redundant sensors based on different technologies are recommended. This strategy would consist of using, for example, an ultrasonic meter and a pressure sensor in a storage facility to ensure water level monitoring in all conditions and to maximize the availability of measurements for safe infrastructure operation.

3.3 Flow Monitoring

Operators can use several technologies and methods of flow monitoring to better understand the characteristics of their collection systems.

3.3.1 Physical Flow Monitoring

Typical commercial flow meters available on the market include ultrasonic Doppler devices, acoustic Doppler sensors, transit time effect sensors, and newer technologies such as Doppler radar sensors and laser Doppler meters. Flow meter technology has been developed to fit a variety of applications; submerged and "non-contacting" devices (sensors located above the water surface) are available. Transit time effect technologies consist exclusively of installing one or multiple pairs of probes (a pair includes one transmitter and one receiver) in a crossing path within the water stream. These probes can measure water velocity at different layers in the conduit to compute flow values according to water level and pipe section. Submerged technologies are generally recognized as being more accurate because they can measure the different velocities that can co-exist within a water flow section at the same time, while non-contacting technologies can only measure the velocity from the surface of the water stream.

Practical experiences of wastewater flow monitoring within sewer pipes ranging from 24 inches to 120 inches in diameter and above have shown that submerged flow meter technologies will generally provide measurements with an accuracy from ±10 percent to 20 percent. Non-submerged flow meter technologies will provide flow measurements with an accuracy typically ranging from ±15 percent to 30 percent. The cost for procurement, installation, and maintenance of "non-contacting" devices is lower than submerged technologies. A permanent flow meter installation in sewers typically ranges from $15,000 to $75,000, and can be even higher if significant work is needed for the infrastructures and the electrical utilities. Regular maintenance for cleaning, inspection, and calibration is recommended at least twice a year to keep monitoring reliable and accurate.

3.3.2 Alternative Flow Monitoring Technologies

In some cases, where installing a physical flow meter becomes too complex or expensive, indirect means of flow monitoring can be developed depending on specific hydraulic conditions.

Implementing Monitoring Technology to Improve Operations

The San Antonio Water System (SAWS) recently participated in a study on the use of monitoring to inform cleaning maintenance programs. SAWS equipped 10 high frequency cleanout sites with remote field monitoring units and used analytical software to monitor day-over-day level trend changes and receive messages for trend anomalies. This analysis of the real-time monitoring data detected small but potentially important changes in water levels. These data enabled users to consider actions such as a site inspection or cleaning. Based on the monitoring data, SAWS reduced cleaning frequency by 94 percent in the study areas. Other than a short period in May/June 2016 when nearly 16 inches of rain overwhelmed the SAWS system, there were zero sanitary sewer overflows at the pilot locations.

Level to flow relationship: When pipe flows remain under "free surface flow" conditions, Manning equations can be used to estimate flow (based on water level sensor data) and physical attributes (pipe shape and dimensions, slope, pipe material for the roughness factor) at the level sensor location. However, the flow estimation is invalid when the flow experiences surcharged conditions or backwater effects are present.

Equations of flow under the gate: When modulating gates are used for flow control, gate position and water level data upstream and downstream from the gate can be used to efficiently compute the flow regulated through the gate. The mathematical formula would also consider the gate's hydraulic conditions and physical dimensions, the regulation chamber, and connection pipes. Optimal gate position (i.e., amount of submergence) can vary depending on gate size and flow velocity and must be determined through hydraulic analysis. Based on several facilities' operations using this method, the relative error is under 5 percent during dry flow conditions and around 15 percent in wet weather conditions.

Weir relationship: A common mathematical means of computing flow values uses level monitoring data from a static weir upstream. Specific formulas must be used depending on the shape of the weir, the physical dimensions of the weir (length, width), and the angle of the flow stream according to the weir. This method can provide fairly accurate flow values for weirs under 6 feet in length; weir relationship calculations involve significant uncertainties for longer weirs.

Bending weir relationship: Bending weirs consist of mechanical flap gate devices with pre-determined weights that are designed to maintain a specified water level on the upstream side of the equipment. When inflows cause the upstream level rise, the bending weir reacts by opening to evacuate excess flow. An inclinometer can be installed on the bending weir's flap gate to monitor the angular opening of the mechanical device. Flow can then be estimated using the corresponding flow and weir angle relationship charts provided by the manufacturer.

Flap gate equations: Similar to bending weir relationships, mathematical functions can be developed for computing flows through flap gates. These relationships will require installing an inclinometer on the flap gate and a level meter upstream of the gate. A downstream level meter will also be required for situations where the flap gate can become submerged. Typically, a temporary flow meter calibrates and validates the equation.

Model-based flow computations: Most utilities have developed a calibrated hydrological and hydraulic model (e.g., EPA SWMM 5) to adequately represent their wastewater system. These models are typically used to plan, design, and produce engineering diagnostics. They can be configured for real-time simulations, based on real-time rainfall and level data or forecasted radar rainfall, to provide flow values virtually everywhere within the wastewater collection or stormwater system. A well-calibrated hydraulic model is recognized for providing flow values within an accuracy range from -15 percent to +25 percent (WEF 2011).

3.4 Rainfall Monitoring

A typical rainfall monitoring system deploys a network of spatially located rain gauges that allow for representative measurement of rainfall quantities over a region. As a general rule for guidance, on average, one rain gauge is recommended for every 500 hectares (1,235 acres) of coverage (Campisano et al. 2013), although coverage needs vary depending on local climate and need for predictive accuracy.

Common rain gauges use tipping bucket systems—either optical or mechanical—that count the quantity of rain trapped in a calibrated cylinder. Each bucket tip will count a specific quantity of rain (e.g., 0.005 inch) over a specific time increment.

Such rainfall monitoring can be made available in real time and can be used as inputs to a hydraulic model to compute flow predictions in the sewer collection system. The flow predictions can then be used to determine the time of concentration of the area tributary to the monitoring location. In addition, when combined with radar reflectivity data and rainfall predictions, flow forecasts can be provided with a more accurate level over the entire territory. Generally, rainfall forecasting windows and grid sizes should be proportional to the hydrologic element's longest time of concentration in the tributary collection system where control is desired—e.g., a large combined sewer overflow (CSO). Rainfall forecasts should cover at least two hours ahead.

4. Collection System Optimization

A key benefit of smart data infrastructure is its application in system optimization to maximize existing infrastructure investment and reduce the need for future capital investment. It provides the framework required to optimize the design and O&M of wastewater and stormwater systems by collecting and analyzing large data sets.

There are two types of system optimization. One refers to system improvements that are applied offline (Muleta and Boulos 2007). Some typical examples include raising weirs to reduce overflow discharge, developing best efficiency curves to minimize energy costs and reduce equipment breakdowns, or optimizing the placement of localized stormwater management and green infrastructure control. For example, the EPA SUSTAIN modeling framework uses an optimization approach to identify the least cost and highest benefit solutions to achieve user-defined objectives (U.S. EPA 2009).

The second type of system optimization is applied online to actively manage the operation of wastewater networks and facilities in real time, a process often referred to as "real-time control" (RTC). RTC systems are discussed in greater detail in Section 5 of this document.

Table 1 presents the data used in a smart data infrastructure approach, regardless of optimization type.

Optimizing Collection System Capacity and Performance

The Philadelphia Water Department (PWD) has committed to reducing 7.9 billion gallons of overflows in the city by 2036 through better stormwater runoff management. As part of this effort, PWD, in collaboration with a private corporation, implemented smart data technology to monitor and maximize the performance of an existing stormwater retention basin. The existing basin was retrofitted with technology to monitor basin water level and precipitation, as well as to provide real-time active control to selectively discharge from the basin during optimal times, effectively increasing the useful capacity of the asset.

Table 1. Data Required to Optimize the Design, Operation, and Maintenance of Wastewater and Stormwater Systems

Objective	Cause of Problem	Potential Intervention	Data Required for System Optimization
Eliminate sanitary sewer overflows	• Rainfall-derived I/I • Undersized pipes	• Pipe replacement • I/I mitigation measures	• Level and flow measurements • Sewer and land characteristics • Cost of potential interventions
	• Grease, debris, and sedimentation buildup	• Improved operating procedures • Pipe replacement • Cleaning (pipes streets) • Flushing systems	• Level, velocity, and flow measurements • Camera inspection • Cost of potential interventions
	• Pipe breaks • Leaking manholes • Offset joints	• Repairs • Pipe replacement	• Flow measurements • Camera inspections • Smoke testing • Cost of potential interventions
Minimize operating costs	• High electricity consumption for pumps and gate operation	• Pump replacement • Use of variable frequency drives • Improved set points • Improved controller parameters	• Time-of-use electricity tariffs • Level and flow measurements • Critical elevation for basement and street flooding • Gate, pumps, and actuator characteristics • Cost of potential interventions
Minimize maintenance costs	• High equipment and sensor failure rate	• Repairs • Replacement • Re-localization • Preventive and predictive maintenance • Best efficiency point	• Level and flow measurements • Equipment and sensor history • Equipment inventory and cost • Detailed alarms • Maintenance and calibration history • Cost of potential interventions
	• Sedimentation issues	• Improved operating level • Sewer modification to increase velocities • Flushing devices	• Level and velocity measurements • Camera inspections • Cost of potential interventions
Minimize CSOs	• Rainfall-derived inflow • Undersized facilities (conveyance, storage treatment)	• Upgrade of existing facilities • Addition of green and grey infrastructure • RTC implementation	• Level and flow measurements • Sewer and land characteristics • Operational and physical constraints • Cost of potential interventions
Reduce flooding risks	• Rainfall-derived inflow • Undersized facilities (conveyance, storage)	• Upgrade of existing facilities • Addition of green and grey infrastructure • RTC implementation	• Level and flow measurements • Sewer and land characteristics • Operational and physical constraints • Critical elevation for basement and street flooding • Cost of potential interventions

4.1 Capacity Management Operation and Maintenance and I/I Control

Optimizing the performance of the collection system is the key component in capacity management operation and maintenance (CMOM) programs. CMOM programs combine standard O&M activities with an increased level of data gathering and information management to more effectively operate collection systems. Smart data infrastructure, equipped with the data input tools described in Section 3, can help accomplish this. Successful CMOM programs are used to identify and mediate capacity-related issues in a system, reducing the risk of system failures such as sanitary sewer overflows (SSOs).

CMOM includes I/I control, the process by which unintended clearwater sources (e.g., groundwater and excess stormwater) exceed the design capacity of a collection system, typically due to antiquated, deteriorating, or inadequately maintained infrastructure. Long-term flow and level metering data can be analyzed to determine performance trends over a long period of time. Historical trends of I/I peak flow rates and volumes can be used to identify areas with high rates of I/I, prioritize removal efforts, and evaluate the costs/benefits of those efforts.

Real-time flow rate and level data collection can be used to identify localized capacity limitations, blockages, and sediment accumulation. These data can then inform more proactive management approaches that can reduce overflows in both dry and wet weather conditions. Such approaches help ensure that the collection system capacity is maximized for wastewater conveyance, which is a critical component of all CMOM programs. In addition to direct monitoring, flow rate and level metering data can be used along with asset management data to predict the "unmetered" portions of a collection system and determine other areas at risk of capacity-related issues, such as high I/I.

Facilities can use smart data infrastructure tools—such as real-time metering and information analysis—to understand the different variables that impact collection system capacity and performance. This knowledge would allow utilities to better plan for necessary capital expenditures and optimize system performance for current and future needs.

Using Smart Data Infrastructure and RTC to Reduce CSOs

Louisville Metropolitan Sewer District (MSD) was an early adopter of RTC, applying inline storage since the 1990s and pioneering the application of global optimal and predictive RTC that has been in operation since 2006. The RTC system is key to maximizing the MSD's conveyance, storage, and treatment capacity to reduce CSOs, with consistent operational results capturing more than 1 billion gallons of CSO volume annually. Incorporating RTC into MSD's LTCP has resulted in approximately $200 million in savings compared to traditional methods.

5. Real-Time Control Systems

RTC can be broadly defined as a system that dynamically adjusts facility operations in response to online measurements in the field to maintain and meet operational objectives during both dry and wet weather conditions (U.S. EPA 2006).

Wastewater systems are often purposefully oversized to provide a factor of safety. This extra capacity can provide short-term storage in the conveyance and treatment system when rain falls unevenly across the collection system and varying runoff lag times that introduce stormwater into the system. RTC presents opportunities to optimize full system capacity for both existing and proposed facilities. Potential benefits include receiving water quality protection, energy savings (Tan et al. 1988), flow equalization, reduced flooding, integrated operations, and better facility planning (Gonwa et al. 1993). Real-time or near real-time reporting can also help utilities meet the public notification requirements for CSO and SSO discharges.

A well-designed RTC system can address a number of different operational goals at different times. Examples of operational goals include (U.S. EPA 2006):

- Reducing or eliminating sewer backups and street flooding.
- Reducing or eliminating SSOs.
- Reducing or eliminating CSOs.
- Managing/reducing energy consumption.
- Avoiding excessive sediment deposition in the sewers.
- Managing flows during a planned (anticipated) system disturbance (e.g., major construction).
- Managing flows during an unplanned (not anticipated) system disturbance, such as major equipment failure or security-related incidents.
- Managing the rate of flow arriving at the wastewater treatment plant.

The application of RTC in a stormwater system is similar to that of a wastewater system. It requires continuous monitoring (e.g., water level, rainfall, weather forecast), control devices (e.g., valves, gates), and data communication to actively manage flows and adapt to changing conditions. If required, temperature, infiltration rate, and water quality parameters (e.g., total suspended solids, nitrogen) can be monitored in real time and integrated into the RTC management strategy. Associated benefits of RTC application in stormwater management include:

- Optimizing the design and sizing of control measures.
- Reducing the frequency of flooding.
- Improving water quality with extended residence time.
- Increasing stormwater harvesting and reuse.
- Adapting to evolving conditions through operation change rather than new infrastructure.
- Providing auditable performance and supporting data from the monitoring system components without additional costs.
- Reducing O&M costs by issuing alerts in real time.

Using RTC to Maximize Capacity and Performance

In 2008, the city of South Bend, Indiana, installed and commissioned a real-time monitoring system of more than 120 sensor locations throughout the city. In 2012, the city and its partners commissioned and distributed a globally optimal RTC system to maximize the capacity and performance of the city's collection system. Since 2012, the city has added additional sensor locations and rain gauges, bringing the total number to 152 sites. It also added automated gates at several stormwater retention basins to better control when and at what rate stormwater is released downstream into the combined system. In the period from 2008 through 2014, South Bend eliminated illicit dry weather overflows and reduced its total CSO volume by roughly 70 percent, or about 1 billion gallons per year.

5.1 Components of an RTC System

Figure 3 presents a typical layout of the components that might be included within an RTC system. Some components are essential for RTC (e.g., sensors, meters), while others may be optional depending on the desired level of control. The components are represented with boxes, and the arrows that connect them indicate the communications and data that are passed on between the components.

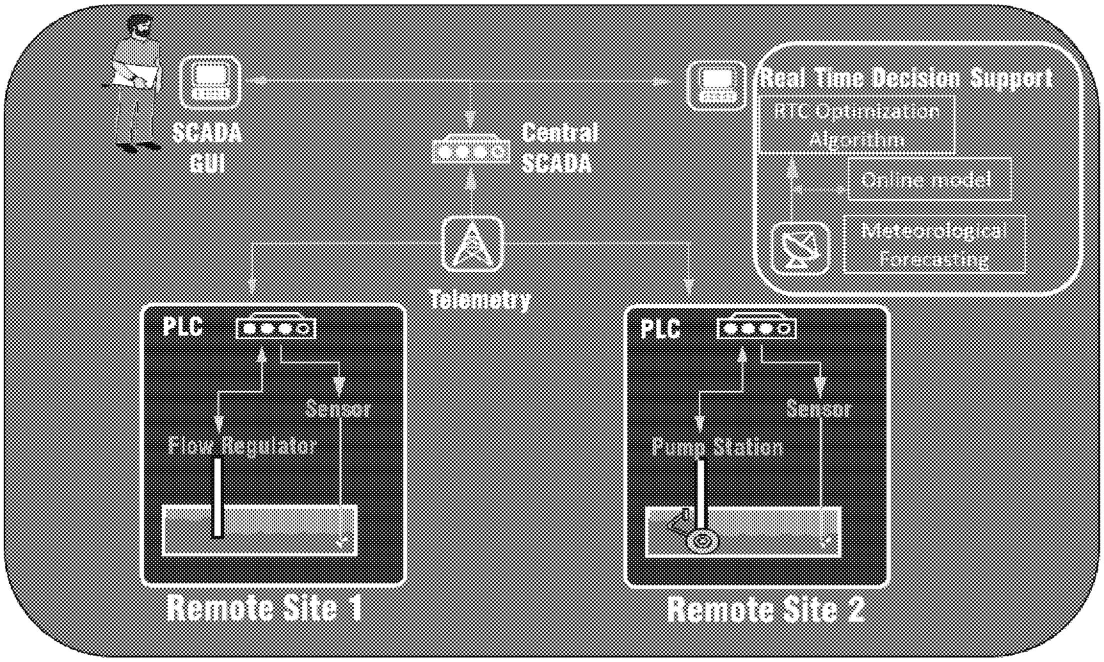


Figure 3. Components of an RTC system

An RTC system, at a minimum, includes sensors that measure the process, control elements that adjust the process, and data communication between them (Schilling 1989). Typical control elements for a wastewater system are regulators, such as pumps (constant or variable speed drives), gates (sluice, radial, sliding, inflatable), and adjustable weirs (bending weir, weir gates).

At each remote site, sensors are connected to the inputs of the local RTC device—in most cases, a programmable logic controller (PLC) or remote terminal unit. The PLC provides outputs (control set points and signals) to the control elements (e.g., gates, pumps) based on the rules embedded (programmed) into the PLC. These rules are feedback algorithms, where action is based on the difference between a set point and the measured variable. For example, a PLC may be programmed to maintain a certain level in the wet well and will reduce the flow through the pump if the level is too low or increase it if the level is too high. The PLC programs can include set points that are defined locally and receive "remote" set points from a central server.

5.1.1 Supervisory Control and Data Acquisition Systems

Supervisory control and data acquisition (SCADA) systems have become more prevalent in the wastewater industry for collecting and managing monitoring data. SCADA is a control system architecture that uses computers, networked data communications, and graphic user interfaces for high-level process supervisory management. Large SCADA systems have evolved to be increasingly similar in function to distributed control systems, which are widely used for process control at the treatment plants. SCADA system designs have taken full advantage of advances in information technology (IT) to collect, archive, and process large amounts of data.

A SCADA system's fundamental purpose is to communicate data and control commands from a centrally located operator to geographically dispersed remote locations in real time. The communication technology options include telephone-based transmission (used in early SCADA systems due to low cost), fiber-optic cable, radio system, cellular-based communication, wireless internet access, and satellite-based systems.

Designing a SCADA system depends on a wide range of practical considerations, including but not limited to equipment enclosures, environmental conditioning, field interface wiring, system documentation requirements, system testing requirements, IT requirements, and cybersecurity.

As utilities invest in continuous monitoring and SCADA, the generated data must be regarded as an important investment to extract maximum values. According to the U.S. Geological Survey, "poor data quality, redundant data, and lost data can cost organizations 15 percent to 25 percent of their operating budget" (USGS n.d.).

Information captured in the field needs to be communicated from the remote stations to the computers and systems that will process, store, and archive it. The SCADA system is considered the backbone of an RTC system. It includes standard graphical user interface (GUI) tools that operators can access, and it allows them to manually override any remote site control actions at any time. As the needs for real-time or near real-time public notifications rise, centralized data management can facilitate data sharing and enable greater transparency.

RTC and CSO Control

The Metropolitan Sewer District of Greater Cincinnati (MSDGC) has one of the most challenging collection systems in the country to manage during wet weather, as it contains more than 200 CSO points. Together, these overflows discharge over 11 billion gallons of sewage into the Ohio River and its tributaries annually. In 2014, MSDGC began installing sensors throughout its largest watershed. By early 2016, MSDGC had gained both real-time visibility and control of its wastewater system in this watershed and transformed the wastewater collection system into a "smart sewers" network. To date, MSDGC's smart sewer system covers over 150 square miles (approximately half) of its service area, incorporating two major treatment plants, six wet weather storage and treatment facilities, four major interceptor sewers, 164 overflow points, and 32 rain gauges and river level sites. Remote monitoring has improved the maintenance of wet weather facilities and enabled upstream facilities to account for downstream interceptor conditions, increasing overflow capture basin-wide during wet weather.

5.2 Real-Time Decision Support Systems

A real-time decision support system (RTDSS) generally overlays the SCADA system. It is connected to the SCADA database to retrieve system status information. An RTDSS can use a SCADA historian and GUI to program and display system status and trends (e.g., abnormal flow, critical water level alarm) or provide additional dashboards involving data analytics to support O&M decision-making. In an RTC system, an RTDSS performs complex calculations based on information inputs to inform operational decisions and help determine optimal system set points (e.g., flow to be pumped, water level to be maintained in a wet well or pipe length).

Typically, decision support uses advanced computing algorithms that are interactive and multi-objective and often involve using an online model for weather forecasting.

5.3 Level of Control

The RTC system can be automated with a centralized or distributed control technology. The main difference is the control and the input/output subsystems. In distributed control architectures, the number and quality of central processing units (CPUs) is determined by the number of modules. Each module has a controller, and the system usually features a central master PLC. The module PLCs automate their respective areas and usually do not include visualization features.

A central architecture usually features a computer, which deals with all tasks such as input/output connections, PLC, and control. Computing capacity, therefore, must be significantly higher than that of a distributed control technology system. There is only one CPU, which means that only one such spare part is needed. RTC system design criteria drive the selection of a control system platform based on the physical and logical components of the system.

Regardless of the control platform, RTC can be implemented using different levels of control, including local, regional, and global. The levels of control are classified according to progressive increases in complexity, performance, and benefits (Schütze et al. 2004).

These set points can be displayed to the operator for manual control or be sent back to the SCADA system in real time for automated control of remote sites. The algorithms used to determine control logics and set points vary in complexity from simple operating rules to complex mathematical optimization techniques (Garcia-Gutierrez et al. 2014).

Local control, or a local reactive control system, is the simplest form of automatic control. Local control is used to solve specific issues that only require information collected near a regulator and is usually implemented as single-input, single-output feedback loop designed to maintain prescribed set points (e.g., flow or level set points). It is a good solution only if the control objectives pursued can be reached without transferring any information between other remote sites.

Regional control is similar to local control except that a telemetry system is required to exchange data with other remote sites. Regional control can be implemented as a distributed or centralized system built on a SCADA system. Some municipalities design their own decision support system to control the collection system based on the specific constraints and opportunities of each control site. However, the control remains reactive, not predictive. Based on a reactive process, there are limitations in the distances between the control structures and measurements; as such, the operation must remain conservative and suboptimal.

Global control is necessary when the control objectives require strong coordination of the control actions at numerous remote sites on a system-wide level. The set points are usually computed and refreshed periodically (e.g., every five to 15 minutes). The global strategy used to determine the set points includes rule-based and optimization-based techniques (Figure 4). Rule-based control considers possible scenarios that can occur during wastewater system operation and determines appropriate control actions based on experience. The rules are generally easy for operators to implement and understand. However, the quality and the performance of those rules highly depend on the available expert knowledge. For large and complex wastewater systems, the strategy may demand many rules.